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(54) **APPARATUS AND METHODS EMPLOYING LIQUID-IMPREGNATED SURFACES**

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CPC *C09D 5/1681* (2013.01); *Y10T 428/13* (2015.01); *Y10T 428/24355* (2015.01); *Y10T 428/24802* (2015.01)

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CPC C09D 5/1681; Y10T 428/24802; Y10T 428/13; Y10T 428/24355

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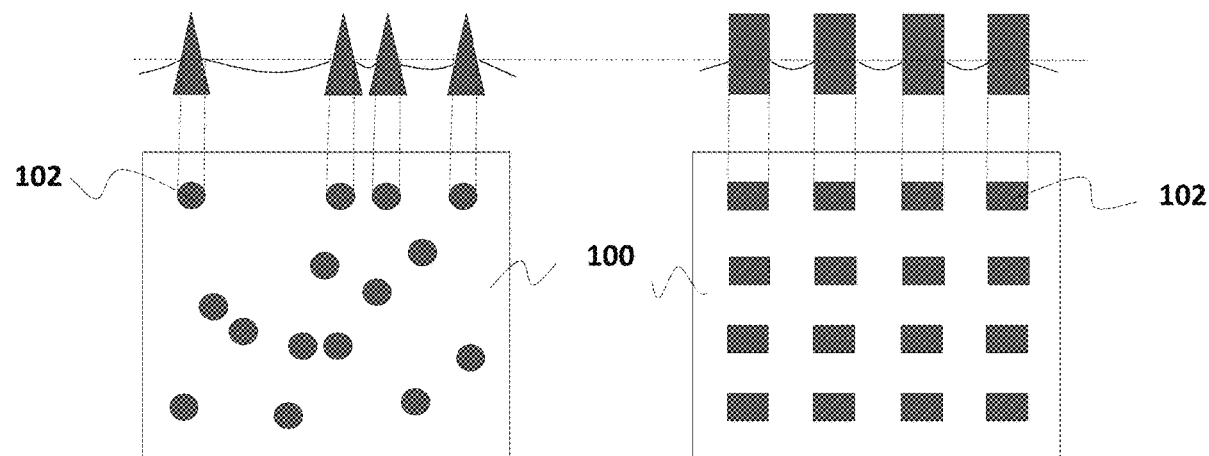
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(57) **ABSTRACT**

In certain embodiments, the invention is directed to apparatus comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, and methods thereof. In some embodiments, one or both of the following holds: (i) $0<\phi\le0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium; and (ii) $S_{ow(a)}<0$, where $S_{ow(a)}$ is spreading coefficient, defined as $\gamma_{wa}-\gamma_{wo}-\gamma_{oa}$, where γ is the interfacial tension between the two phases designated by subscripts w, a, and o, where w is water, a is air, and o is the impregnating liquid.

15 Claims, 6 Drawing Sheets

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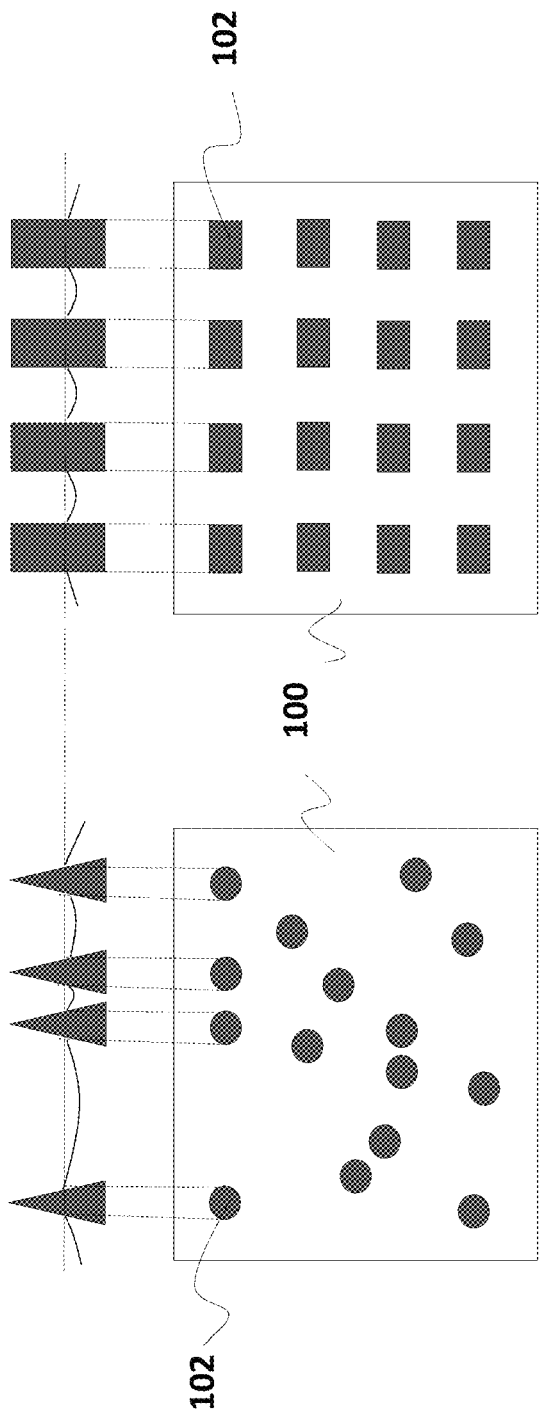
FIG. 1
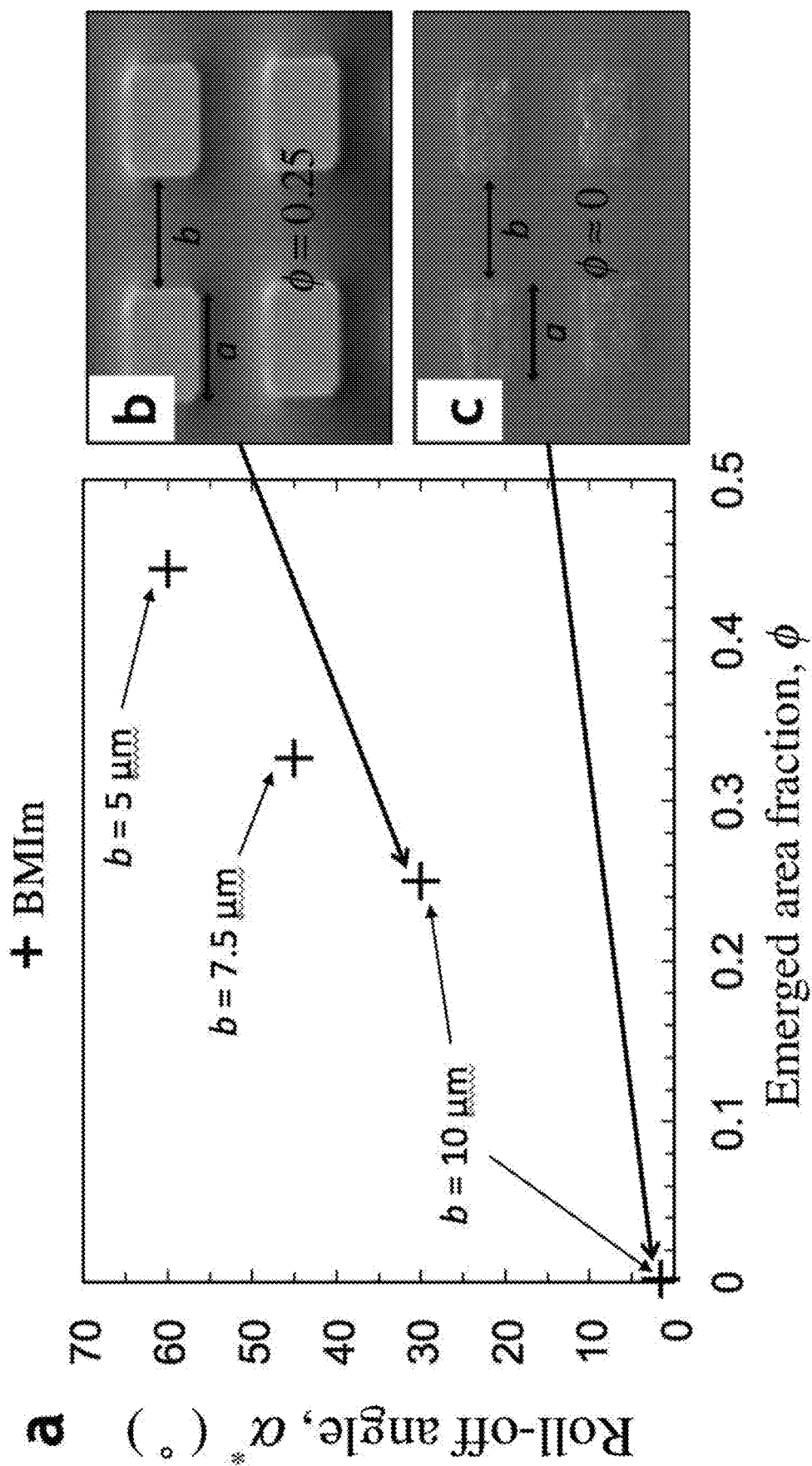
FIG. 2
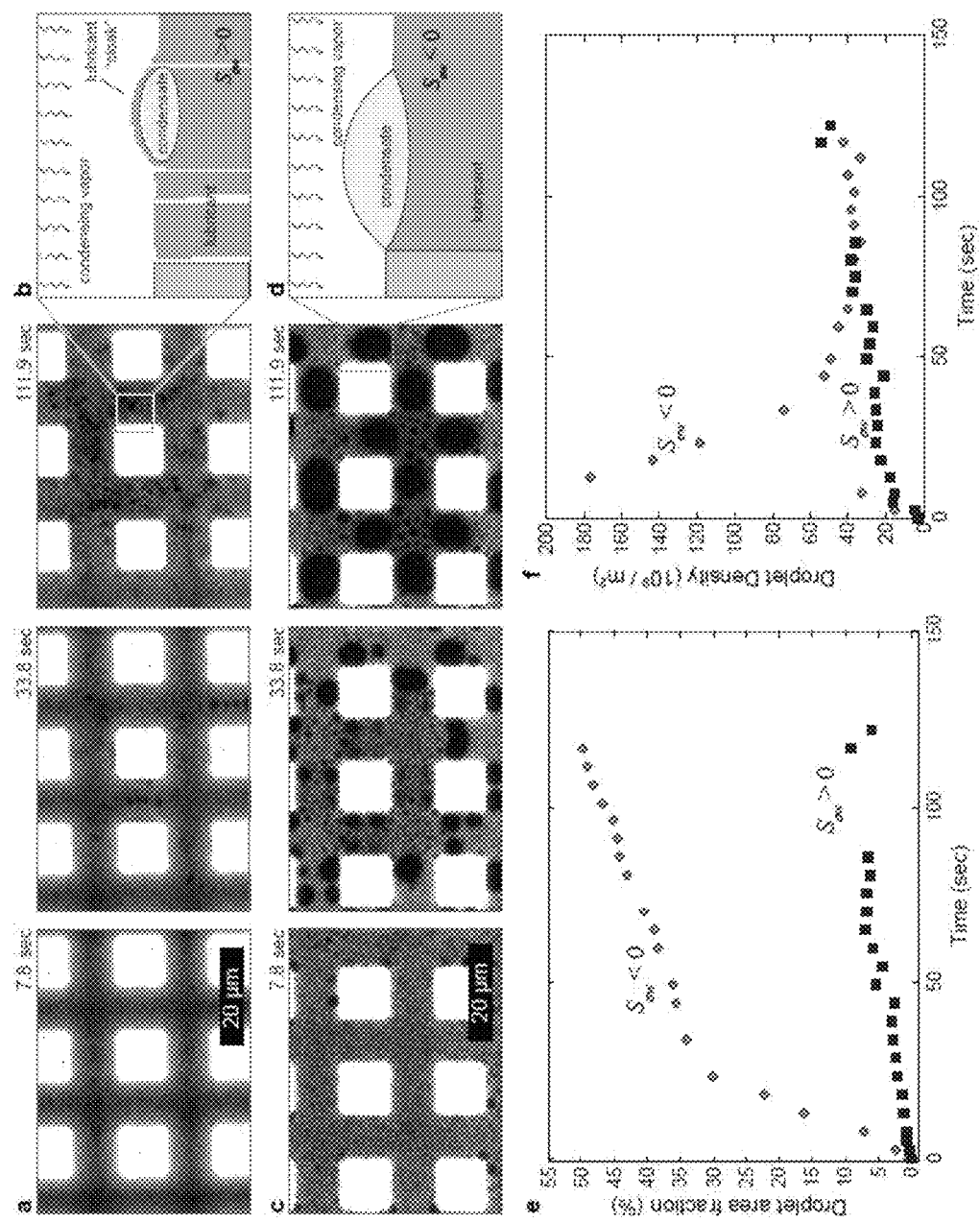
FIG. 3

10 cSt Silicon Oil

100 cSt Silicon Oil
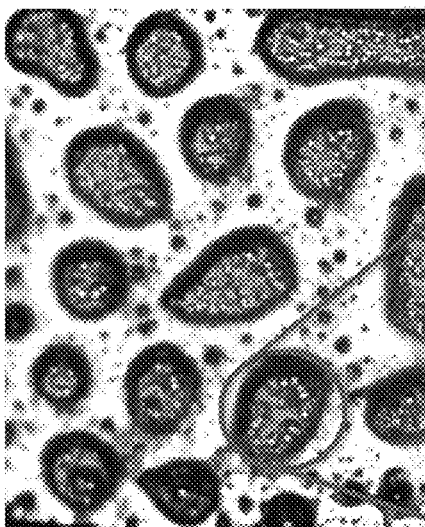
The bright white spots visible here are water droplets that are not coalescing with the bigger droplet due to lubricant layer between them
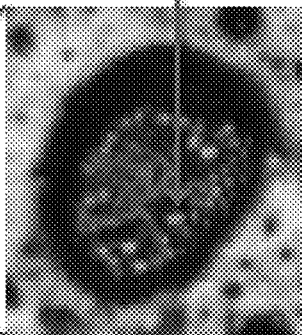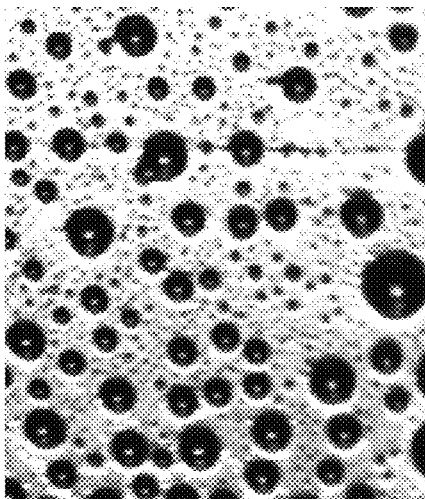
FIG. 4
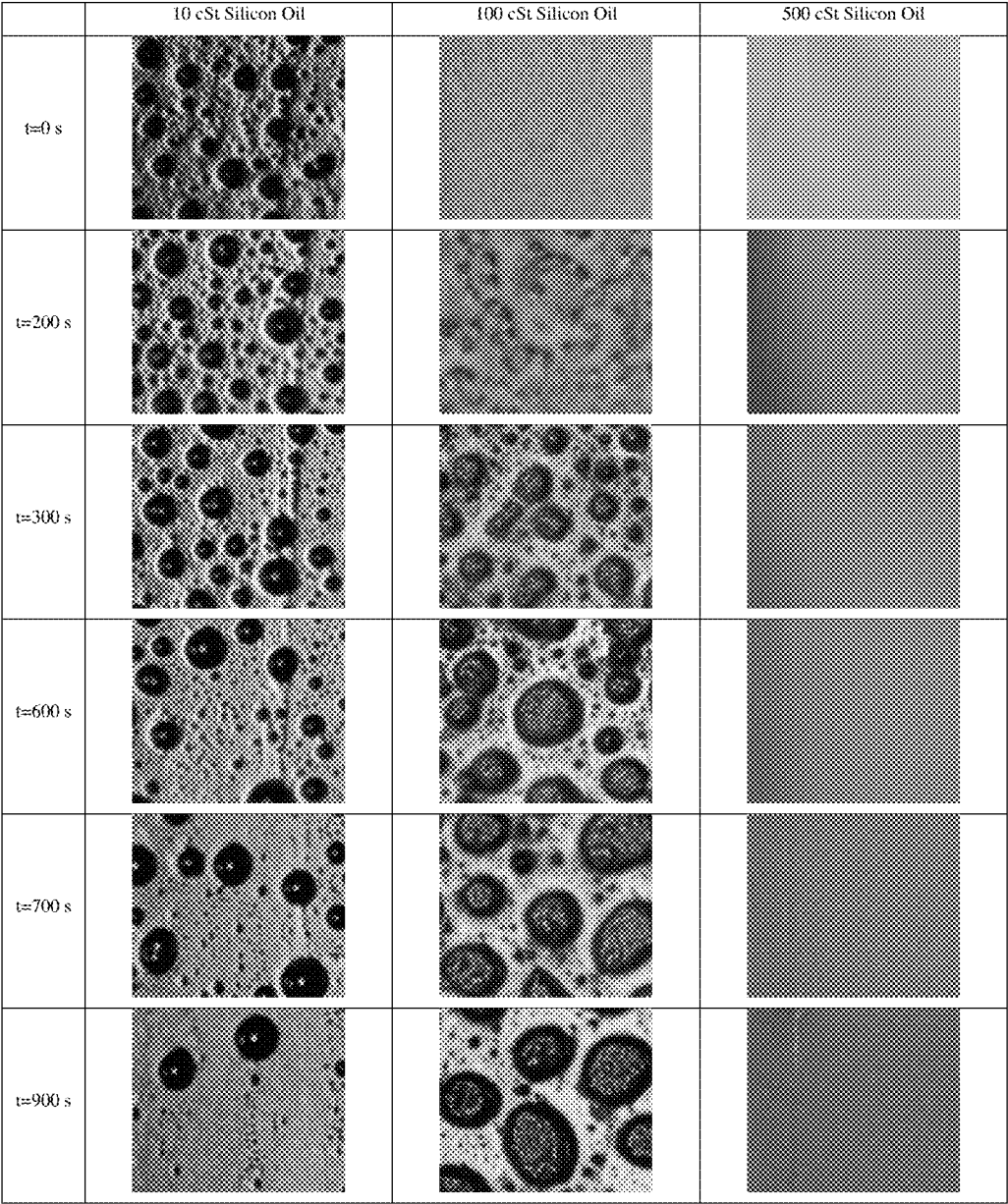
FIG. 5
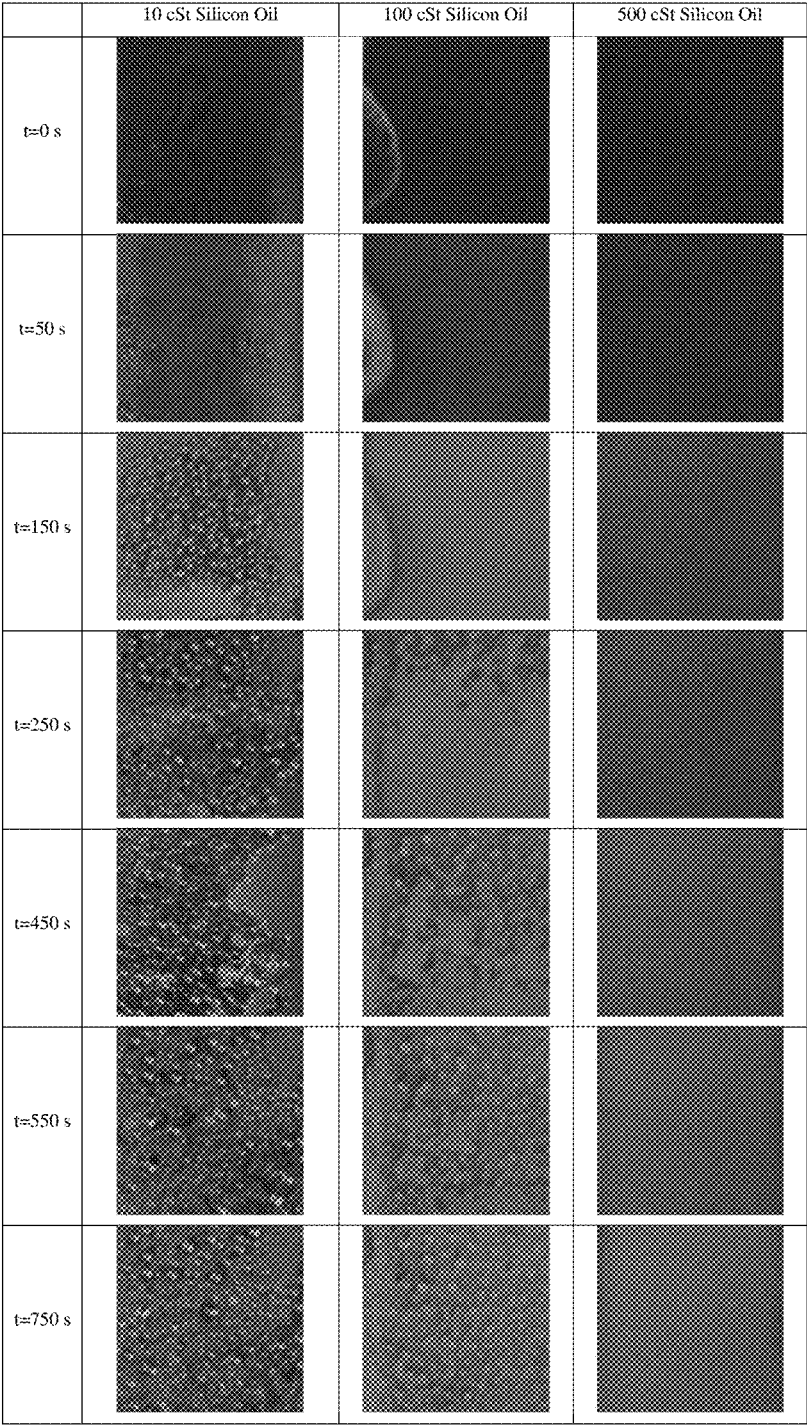
FIG. 6

APPARATUS AND METHODS EMPLOYING LIQUID-IMPREGNATED SURFACES

RELATED APPLICATIONS

This is a continuation of U.S. Non-Provisional application Ser. No. 14/084,126, filed Nov. 19, 2013, which claims the benefit of U.S. Provisional Patent Application No. 61/728,219, which was filed on Nov. 19, 2012, each incorporated herein by reference.

TECHNICAL FIELD

This invention relates generally to non-wetting and low adhesion surfaces. More particularly, in certain embodiments, the invention relates to non-wetting, liquid-impregnated surfaces that are engineered to eliminate pinning and/or to either avoid or induce cloaking.

BACKGROUND

The advent of micro/nano-engineered surfaces in the last decade has opened up new techniques for enhancing a wide variety of physical phenomena in thermofluids sciences. For example, the use of micro/nano surface textures has provided nonwetting surfaces capable of achieving less viscous drag, reduced adhesion to ice and other materials, self-cleaning, and water repellency. These improvements result generally from diminished contact (i.e., less wetting) between the solid surfaces and adjacent liquids.

One type of non-wetting surface of interest is a superhydrophobic surface. In general, a superhydrophobic surface includes micro/nano-scale roughness on an intrinsically hydrophobic surface, such as a hydrophobic coating. Superhydrophobic surfaces resist contact with water by virtue of an air-water interface within the micro/nano surface textures.

One of the drawbacks of existing non-wetting surfaces (e.g., superhydrophobic, superoleophobic, and supermetallophobic surfaces) is that they are susceptible to impalement, which destroys the non-wetting capabilities of the surface. Impalement occurs when an impinging liquid (e.g., a liquid droplet or liquid stream) displaces the air entrained within the surface textures. Previous efforts to prevent impalement have focused on reducing surface texture dimensions from micro-scale to nano-scale.

Although not well recognized in previous studies of liquid-impregnated surfaces, the impregnating liquid may spread over and "cloak" the contacting liquid (e.g., water droplets) on the surface. For example, cloaking can cause the progressive loss of impregnating liquid through entrainment in the water droplets as they are shed from the surface.

There is a need for non-wetting surfaces that are robust and/or deliver optimal non-wetting properties.

SUMMARY OF THE INVENTION

Described herein are non-wetting surfaces that include a liquid impregnated within a matrix of micro/nano-engineered features on the surface, or a liquid filling pores or other tiny wells on the surface. In certain embodiments, compared to previous non-wetting surfaces, which include a gas (e.g., air) entrained within the surface textures, these liquid-impregnated surfaces are resistant to impalement and frost formation, and are therefore more robust.

Impregnating fluids that cover the tops of the matrix of solid features offer a non-wetting benefit. However, at

equilibrium, the impregnating liquid may not cover the tops of solid features (e.g., microposts or nanograss) of the surface without being continually replenished. Furthermore, while certain impregnating fluids do cover the tops of solid features, offering a non-wetting benefit, they often exhibit cloaking, and the impregnating fluid is depleted unless replenished.

It is discovered that liquid-impregnated surfaces can be engineered to provide resistance to impalement and to provide non-wettability, without requiring replenishment of impregnating fluid to make up for liquid lost to cloaking, and without requiring replenishment of impregnating liquid to maintain coverage over the tops of the solid features.

In one aspect, the invention includes an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $0 < \phi \le 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium; and (ii) $S_{ow(a)} < 0$, where $S_{ow(a)}$ is spreading coefficient, defined as $\gamma_{wa} - \gamma_{wo} - \gamma_{oa}$, where γ is the interfacial tension between the two phases designated by subscripts w, a, and o, where w is water, a is air, and o is the impregnating liquid.

In certain embodiments, ϕ is in a range of 0 to 0.25. In certain embodiments, ϕ is in a range of 0 to 0.10. In certain embodiments, ϕ is in a range of 0.001 to 0.25. In certain embodiments, ϕ is in a range of 0.001 to 0.10.

In certain embodiments, $S_{ow(a)} < 0$.

In certain embodiments, the impregnating liquid comprises an ionic liquid (e.g., impregnating liquids that do not exhibit cloaking in the presence of air and water). Exemplary impregnating liquid includes at least one member selected from the group consisting of tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene, perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, and amyl phthalate.

In certain embodiments, the solid features include at least one member selected from the group consisting of a polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid. In certain embodiments, the solid features comprise a chemically modified surface, coated surface, surface with a bonded monolayer.

In certain embodiments, the solid features define at least one member selected from the group consisting of pores, cavities, wells, interconnected pores, and interconnected cavities. In certain embodiments, the solid features include at least one member selected from the group consisting of posts, nanoneedles, nanograss, substantially spherical particles, and amorphous particles.

In certain embodiments, the solid features have a roughened surface. In certain embodiments, the roughened surface provides stable impregnation of liquid therebetween or therewithin, such that $\theta_{os(v), \, receding} < \theta_c$.

In certain embodiments, the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface and have a roll-off angle α of less than 40° (e.g, for a 5 microliter droplet). In certain embodiments, the water droplets have a roll-off angle α of less than 25° (e.g., for a 5 microliter droplet).

In certain embodiments, $\theta_{os(v),\ receding} > 0$.

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(w),receding} = 0$ (e.g., useful for 3-phase systems such as inside a pipeline-impregnating liquid phase, solid phase, and pipeline liquid (e.g. oil) phase-specification will define $\theta_{os(w),receding}$); and (ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(w),receding} = 0$ (e.g., useful for 4-phase systems such as surfaces exposed to liquid droplets in air-impregnating liquid phase, solid phase, droplet phase, air phase—specification will define $\theta_{os(w),receding}$ and $\theta_{os(v),receding}$). In certain embodiments, one or more previously described features may apply to various embodiments in this aspect of the invention.

In another aspect, the invention includes a method of utilizing a liquid-impregnated surface. The method includes the steps of: providing an article comprising a liquid-impregnated surface having $0 < \phi \leq 0.25$ at equilibrium, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid; and using the article at equilibrium or pseudo equilibrium. In certain embodiments, equilibrium is a relative term—e.g. some evaporation of impregnating liquid may be occurring, but the article is still considered to be "at equilibrium".

In certain embodiments, ϕ is a range of 0.001 to 0.25. In certain embodiments, ϕ is in a range of 0.01 to 0.25. In certain embodiments, at least one of the following holds: (i) $\theta_{os(v),\ receding} > 0$; and (ii) $\theta_{os(w),\ receding} > 0$. In certain embodiments, one or more previously described features may apply to various embodiments in this aspect of the invention.

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(v),\ receding} > 0$; and (ii) $\theta_{os(w),\ receding} > 0$.

In certain embodiments, both $\theta_{os(v),\ receding} > 0$ and $\theta_{os(w),\ receding} > 0$. In certain embodiments, one or more previously described features may apply to various embodiments in this aspect of the invention.

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(v),receding} < \theta_c$; and (ii) $\theta_{os(w),receding} < \theta_c$.

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(v),receding} < \theta^*_c$; and (ii) $\theta_{os(w),receding} < \theta^*_c$, where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface. In certain

embodiments, one or more previously described features may apply to various embodiments in this aspect of the invention.

In another aspect, the invention includes a method of utilizing a liquid-impregnated surface, the method comprising the steps of: providing an article described herein; and using the article at equilibrium or pseudo-equilibrium (e.g., wherein the properties specified in the claim hold true at equilibrium).

In certain embodiments, the article is used in a three-phase system. (e.g., impregnating liquid phase, solid surface phase, and contacting liquid phase, e.g., a pipeline). In certain embodiments, the article is used in a four-phase system (e.g., impregnating liquid phase, solid surface phase, droplet phase, and surrounding gas phase). In certain embodiments, the article is a pipeline or portion or coating thereof. In certain embodiments, the article is a member selected from the group consisting of a steam turbine part, a gas turbine part, an aircraft part, a wind turbine part, eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part (e.g., piston or cylinder), or a portion or coating thereof.

In another aspect, the invention includes a method of utilizing a liquid-impregnated surface, the method comprising the steps of: providing an article comprising a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, said impregnating liquid and said matrix chosen such that S>0, whereby the impregnating liquid cloaks clusters upon their nucleation on the surface and restricts access of said clusters to their source medium surrounding the surface (e.g., where the cloaked clusters are condensed water droplets or bacterial colonies); and using the article at equilibrium or pseudo equilibrium, thereby preventing or inhibiting one or more of: ice/frost formation on the surface, bacterial growth on the surface, formation of liquid condensate on the surface, and fouling of the surface.

In certain embodiments, the impregnating liquid has viscosity greater than 50 cP. In certain embodiments, the impregnating liquid has viscosity greater than 100 cP. In certain embodiments, the impregnating liquid has viscosity greater than 300 cP (e.g., viscosity is about 500 cP or more).

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, said impregnating liquid and said matrix chosen such that S>0, whereby the impregnating liquid cloaks clusters upon their nucleation on the surface and restricts access of said clusters to their source medium surrounding the surface (e.g., where the cloaked clusters are condensed water droplets or bacterial colonies), thereby preventing or inhibiting one or more of: ice/frost formation on the surface, bacterial growth on the surface, formation of liquid condensate on the surface, and fouling of the surface.

In certain embodiments, the impregnating liquid has viscosity greater than 50 cP, 100 cP, or 300 cP (e.g., about 500 cP or more).

In another aspect, the invention includes an article comprising a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, said impregnating liquid having viscosity greater than about

50 cP, 100 cP, or 300 cP (e.g., about 500 cP or more), thereby inhibiting formation of frost on the surface.

In another aspect, the invention includes a method of inhibiting frost formation on a surface, the method comprising: providing a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, said impregnating liquid having viscosity greater than about 50 cP, 100 cP, or 300 cP (e.g., about 500 cP or more); and using the article at equilibrium or pseudo equilibrium.

In another aspect, the invention includes an article comprising an interior surface, said article being at least partially enclosed (e.g., the article is an oil pipeline, other pipeline, consumer product container, other container) and adapted for containing or transferring a fluid of viscosity μ_1, wherein the interior surface comprises a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein the impregnating liquid comprises water (having viscosity μ_2) (e.g., wherein the impregnating liquid is at least 50%, 60%, 70%, 80%, or 90% water) (e.g., "droplet phase" has higher viscosity than impregnating liquid (lubricant)—droplet slides instead of rolls, resulting in drag reduction).

In certain embodiments, $\mu 1/\mu 2$ is greater than 1. In certain embodiments, $\mu 1/\mu 2$ is greater than 0.1.

In certain embodiments, $(h/R)(\mu_1/\mu_2)$ is greater than 0.1, where h is the average height of the solid features and R is the radius of the pipe or the average fluid depth in an open system. In certain embodiments, $(h/R)(\mu_1/\mu_2)$ is greater than 0.5. In certain embodiments, R is less than 1 mm.

In certain embodiments, the impregnating liquid comprises an additive to prevent or reduce evaporation of the impregnating liquid. In certain embodiments, the additive is a surfactant.

In another aspect, the invention includes a method comprising providing the article described herein and using the article to transfer or contain the fluid of viscosity μ_1.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the invention can be better understood with reference to the drawing described below, and the claims.

FIG. 1 illustrates a schematic cross-sectional and corresponding top view of a liquid-impregnated surface that are partially submerged.

FIG. 2 includes a plot of roll-off angle versus emerged area fraction ϕ and two SEM images of BMIm impregnated texture, in accordance with certain embodiments of the invention.

FIG. 3 and FIG. 4 demonstrate condensation inhibition by preventing coalescence due to liquid cloaking, in accordance with certain embodiments of the invention.

FIG. 5 demonstrates condensation inhibition by less nucleation on high viscosity liquids, in accordance with certain embodiments of the invention.

FIG. 6 demonstrates frost inhibition by less nucleation on high viscosity liquids, in accordance with certain embodiments of the invention.

DESCRIPTION

It is contemplated that compositions, mixtures, systems, devices, methods, and processes of the claimed invention

encompass variations and adaptations developed using information from the embodiments described herein. Adaptation and/or modification of the compositions, mixtures, systems, devices, methods, and processes described herein may be performed by those of ordinary skill in the relevant art.

Throughout the description, where articles, devices, apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are articles, devices, apparatus and systems of the present invention that consist essentially of, or consist of, the recited components, and that there are processes and methods according to the present invention that consist essentially of, or consist of, the recited processing steps.

Similarly, where articles, devices, mixtures, apparatus and compositions are described as having, including, or comprising specific compounds and/or materials, it is contemplated that, additionally, there are articles, devices, mixtures, apparatus and compositions of the present invention that consist essentially of, or consist of, the recited compounds and/or materials.

It should be understood that the order of steps or order for performing certain actions is immaterial so long as the invention remains operable. Moreover, two or more steps or actions may be conducted simultaneously.

The mention herein of any publication, for example, in the Background section, is not an admission that the publication serves as prior art with respect to any of the claims presented herein. The Background section is presented for purposes of clarity and is not meant as a description of prior art with respect to any claim.

In some embodiment, a non-wetting, liquid-impregnated surface is provided that includes a solid having textures (e.g., posts) that are impregnated with an impregnating liquid. In general, solid features can be made from or comprise any material suitable for use in accordance with the present invention. In accordance with various embodiments of the present invention, micro-scale solid features are used (e.g., from 1 micron to about 100 microns in characteristic dimension). In certain embodiments, nano-scale solid features are used (e.g., less than 1 micron, e.g., 1 nm to 1 micron).

In some embodiments, the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface.

As used herein, emerged area fraction ϕ is defined as a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium. The term "equilibrium" as used herein refers to the condition in which the average thickness of the impregnating film does not change over time due to drainage by gravity when the substrate is held away from horizontal, and where evaporation is negligible (e.g., if the liquid impregnated liquid were to be placed in an environment saturated with the vapor of that impregnated liquid). Similarly, the term "pseudo-equilibrium" as used herein refers to the same condition except that evaporation may occur.

In general, a "representative fraction" of a surface refers to a portion of the surface with a sufficient number of solid features thereupon such that the portion is reasonably representative of the whole surface. In certain embodiments, a "representative fraction" is at least a tenth of the whole surface.

Referring to FIG. 1, a schematic cross-sectional view and the corresponding top view of a liquid-impregnated surface that is partially submerged is shown. The upper left drawing of FIG. 1 shows a cross-sectional view of a row of cone-shaped solid features. The projected surface area of the non-submerged solid 102 is illustrated as shaded areas of the overhead view, while the remaining non-shaded area represents the projected surface area of the submerged liquid-impregnated surface 100. In addition to the projection surface area of this row of solid features, other solid features placed in a semi-random pattern are shown in shade in the overhead view. Similarly, the cross-section view of a row of evenly spaced posts is shown on the right of FIG. 1. Additional rows of well-patterned posts are shown in shade in the overhead view. As demonstrated, in some embodiments of the present invention, a liquid-impregnated surface includes randomly and/or non-randomly patterned solid features.

In certain embodiments of the present invention, ϕ is less than 0.30, 0.25, 0.20, 0.15, 0.10, 0.05, 0.01, or 0.005. In certain embodiments, ϕ is greater than 0.001, 0.005, 0.01, 0.05, 0.10, 0.15, or 0.20. In certain embodiments, ϕ is in a range of about 0 and about 0.25. In certain embodiments, ϕ is in a range of about 0 and about 0.01. In certain embodiments, ϕ is in a range of about 0.001 and about 0.25. In certain embodiments, ϕ is in a range of about 0.001 and about 0.10.

In some embodiments, the liquid-impregnated surface is configured such that cloaking by the impregnating liquid can be either eliminated or induced, according to different embodiments described herein.

As used herein, the spreading coefficient, $S_{ow(a)}$ is defined as $\gamma_{wa}-\gamma_{wo}-\gamma_{oa}$, where γ is the interfacial tension between the two phases designated by subscripts w, a, and o, where w is water, a is air, and o is the impregnating liquid. Interfacial tension can be measured using a pendant drop method as described in Stauffer, C. E., "The measurement of surface tension by the pendant drop technique," J. Phys. Chem. 1965, 69, 1933-1938, the text of which is incorporated by reference herein. Exemplary surfaces and its interfacial tension measurements (at approximately 25° C.) are shown in Appendix D, in particular, Table S2.

Without wishing to be bound to any particular theory, impregnating liquids that have $S_{ow(a)}$ less than 0 will not cloak, resulting in no loss of impregnating liquids, whereas impregnating liquids that have $S_{ow(a)}$ greater than 0 will cloak matter (condensed water droplets, bacterial colonies, solid surface) and this may be exploited to prevent corrosion, fouling, etc. In certain embodiments, cloaking is used for preventing vapor-liquid transformation (e.g, water vapor, metallic vapor, etc.). In certain embodiments, cloaking is used for inhibiting liquid-solid formation (e.g., ice, metal, etc.). In certain embodiments, cloaking is used to make reservoirs for carrying the materials, such that independent cloaked materials can be controlled and directed by external means (like electric or magnetic fields).

In certain embodiments, lubricant cloaking is desirable and is used a means for preventing environmental contamination, like a time capsule preserving the contents of the cloaked material. Cloaking can result in encasing of the material thereby cutting its access from the environment. This can be used for transporting materials (such as bioassays) across a length in a way that the material is not contaminated by the environment.

In certain embodiments, the amount of cloaking can be controlled by various lubricant properties such as viscosity, surface tension. Additionally or alternatively, we can control

the de-wetting of the cloaked material to release the material. Thus, it is contemplated that a system in which a liquid is dispensed in the lubricating medium at one end, and upon reaching the other end is exposed to environment that causes the lubricant to uncloak.

In certain embodiments, an impregnating liquid is or comprises an ionic liquid. In some embodiments, an impregnating liquid can be selected to have a $S_{ow(a)}$ less than 0. Exemplary impregnating liquids include, but are not limited to, tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene, perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, amyl phthalate and any combination thereof.

In accordance with the present invention, exemplary solid features include, but are not limited to, polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid and any combination thereof. As demonstrated in FIG. 1, solid features can comprise any suitable shapes and/or define any suitable structures. Exemplary solid features include, but are not limited to, pores, cavities, wells, interconnected pores, and interconnected cavities and any combination thereof.

In some embodiments, solid features have a roughened surface. As used herein, $\theta_{os(a)}$ is defined as the contact angle of oil (subscript 'o') on the textured solid (subscript 's') in the presence of air (subscript 'a'). In certain embodiments, the roughened surface of solid features provides stable impregnation of liquid therebetween or therewithin, when $\theta_{os(v)}>\theta_c$.

In certain embodiments, liquid-impregnated surfaces described herein have advantageous droplet roll-off properties that minimize the accumulation of the contacting liquid on the surfaces. Without being bound to any particular theory, a roll-off angle α of the liquid-impregnated surface in certain embodiments is less than 50°, less than 40°, less than 30°, less than 25°, or less than 20°.

Typically, flow through a pipe or channel, having a liquid-impregnated surface on its interior:

$$\frac{Q}{\Delta p/L} \sim \left(\frac{R^4}{\mu_1}\right)\left[1+\left(\frac{h}{R}\right)\left(\frac{\mu_1}{\mu_2}\right)\right] \qquad (1)$$

where Q is the volumetric flow rate, R is pipe radius, h is the height of the texture, μ_2 is the viscosity of lubricant and μ_1 is the viscosity of the fluid flowing through the pipe. $\Delta p/L$ is the pressure drop per L. Without being bound to any particular theory, it is believed that $(h/R)(\mu_1/\mu_2)$ is greater than 1 for this to have a significant effect and this sets the height of the texture in relation to the viscosity ratio.

Although modeled for pipe flow, the general principals also apply to open systems, where R is replaced with the characteristic depth of the flowing material. The average velocity of the flow $\sim Q/A$, where A is the cross-sectional area of the flowing fluid.

Example 3

This Example demonstrates that condensation can be inhibited by limiting nucleation on high viscosity liquids.

Similar to the conditions described in Example 2, the temperature of the peltier cooler was set at $-5°$ C. The room temperature was $20°$ C., and the dew point in the conditions was $12°$ C. As can be seen in FIG. **5**, the condensation rate is significantly decreased as viscosity of the oil increases. This is because the more viscous an oil, the less rapid the deformation of its surface upon adsorption of vapor molecules. Whereas on low viscosity liquids, the more rapid change of curvature upon deformation leads a more rapid decrease in the energy barrier for condensation to proceed, and hence more rapid condensation.

Example 4

This Example demonstrates that frost can be inhibited by limiting nucleation on high viscosity liquids.

Similar to the conditions described above, the temperature of the peltier cooler was set at $-15°$ C. The experiments were conducted in low relative humidity environment such the dew point in the conditions was $-10°$ C. In these conditions, water vapor forms directly as frost on the peltier plate. However, on the impregnated surface, water vapor still forms as droplets, and frost. As can be seen in FIG. **6**, the frost formation rate is significantly decreased as viscosity of the oil increases. On low viscosity liquid, the water phase show mobility signifying that water exists as supercooled droplets.

EQUIVALENTS

While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $0<\phi\le0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium; and

(ii) $S_{ow(a)}<0$, where $S_{ow(a)}$ is spreading coefficient, defined as $\gamma_{wa}-\gamma_{wo}-\gamma_{oa}$, where γ is the interfacial tension

between the two phases designated by subscripts w, a, and o, where w is water, a is air, and o is the impregnating liquid,

wherein the liquid-impregnated surface is non-wetting to a contacting liquid.

2. The article of claim **1**, wherein $0.001<\phi\le0.25$.

3. The article of claim **1**, wherein $0.001<\phi\le0.10$.

4. The article of claim **1**, wherein $S_{ow(a)}<0$.

5. The article of claim **1**, wherein the impregnating liquid comprises an ionic liquid.

6. The article of claim **1**, wherein the impregnating liquid comprises at least one member selected from the group consisting of tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene, perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, and amyl phthalate.

7. The article of claim **1**, wherein the solid features comprise at least one member selected from the group consisting of a polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid.

8. The article of claim **1**, wherein the solid features comprise a chemically modified surface, a coated surface, and/or a surface with a bonded monolayer.

9. The article of claim **1**, wherein the solid features define at least one member selected from the group consisting of pores, cavities, wells, interconnected pores, and interconnected cavities.

10. The article of claim **1**, wherein the solid features comprise at least one member selected from the group consisting of posts, nanoneedles, nanograss, substantially spherical particles, and amorphous particles.

11. The article of claim **1**, wherein the solid features have a roughened surface.

12. The article of claim **1**, wherein $0<\phi\le0.25$.

13. The article of claim **12**, wherein $0<\phi\le0.10$.

14. The article of claim **1**, wherein the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface and have a roll-off angle α of less than $40°$.

15. The article of claim **14**, wherein the water droplets have a roll-off angle α of less than $25°$.

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